2018-06-11

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Singh, Y

http://hdl.handle.net/10026.1/11715

10.1109/ICARSC.2018.8374170
ICARSC 2018: IEEE International Conference on Autonomous Robot Systems and Competitions
Institute of Electrical and Electronics Engineers

Feasibility Study of a Constrained Dijkstra Approach for Optimal Path Planning of an Unmanned Surface Vehicle in a Dynamic Maritime Environment

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***Abstract*—Optimal path planning is an important part of mission management hierarchy in a modern unmanned surface vehicle (USV) guidance, navigation and control frame work. USVs operate in a complex dynamic marine environment comprising of moving obstacles and sea surface currents. These characterising variables of configuration space change spatially as well as temporally. The current work investigates a well-known search technique, the Dijkstra algorithm, to resolve the problem of motion planning for a USV moving in a maritime environment. The current study extends the implementation of Dijkstra algorithm in a space cluttered with static and moving obstacles. In addition, downstream and upstream effects of sea surface currents of different intensities on optimal path planning are studied. The performance is verified in simulations with total path length and elapsed computational time considered as parameters to determine the effectiveness of the adopted approach. The results showed that the approach is effective for global path planning of USVs.**

***Keywords*—Moving obstacles, Ocean current, Path planning, Unmanned surface vehicle .**

I. Introduction

During the last decade, several advancements have taken place in satellite navigation of unmanned surface vehicles (USVs) operating at sea for applications ranging from military scouting in inimical areas to bathymetric surveys of shallow waters [1]. Major development and research in improving the autonomy of USVs started in the 1990s during the Gulf War [2]. Development of efficient and optimal navigation algorithms for USVs becomes a crucial aspect of achieving the objective of higher autonomy.

In order to navigate USVs in a marine environment, several global and local path planning approaches have been proposed based on restrictions imposed by obstacles, USV geometry and nonholonomic constraints [3]. Assuming uncertainties of the marine environment and limited onboard computational capability, the complexity of path planning of USVs becomes exponential. In order to find a practical solution for USV path planning, simplified approaches are required which can guarantee a solution for finding a feasible path. The present paper takes into account a well-known global approach based on graph search method, Dijkstra algorithm [4] for optimal path planning of USVs in the marine environment. Environmental uncertainties of the marine environment in form of sea surface currents and moving obstacles play a major role real-time motion planning of USVs. The current study considers such uncertainties in the understanding effectiveness of optimal path planners in USV path planning.

The plan of the paper is as follows. Section I gives a brief introduction to the USV path planning and current challenges associated with the USV path planning. Section II gives an overview of the literature pertaining to global path planning approaches applied to USVs and the major outcomes of the present study are outlined. Section III provides a brief overview of the Dijkstra algorithm and discussion pertaining to its applicability within the stated problem of USV path planning. Section IV presents the results of the USV navigation using Dijkstra approach. Conclusions and future work of the study are presented in the final section.

II. Review of Literature and Major Contribution

USVs are non-holonomic systems, characterized by differential equations constrained by time derivatives of state variables. Complete planners cannot guarantee a solution for such systems reaching the goal and therefore approximate methods have been found efficient in planning motions for non-holonomic systems. Global grid-based approaches are such approximate methods which guarantee solutions for finding a path if there exists one. Dijkstra initiated the work in the area of grid-map based path planning by studying shortest path between two nodes specified on a map [4] which was later extended and improved in form of A* approach [5]. During the last decade, several improved versions of A* approach have been implemented to understand the performance of USVs in the different marine environment. The first study towards this was proposed by combining A* approach with a local path planner for USV path planning in a constrained harbour [6]. The same approach was extended in the uncertain sea environment to understand the effectiveness of global path planner with uncertainty [7]. USVs need to comply with International Regulations for Preventing Collisions at Sea (COLREGs) in order to operate safely with International Maritime Organisation (IMO) guidelines. One of the initial efforts was made by combining A* approach with rule 14 of COLREGs in an environment cluttered with static and dynamic obstacles [8]. A modified A* approach, Finite Angle A* (FAA*) was proposed later to comply with the heading and safety requirements of the USV [9]. Other A* modifications such as Theta* [10], ARC- Theta* [11] and modified heuristic A* [12] have been applied in USV path planning based on the mission and kinematic requirements of USV.

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Until now in the literature, most studies related to path planning in marine robotics have been in the area of autonomous underwater vehicles (AUVs) [13], [14], [15] and very few studies related with global path planning of USVs have been piloted. AUVs cannot operate in all environmental conditions due to limited speed and onboard capabilities against USVs which are more suited for operation in areas of high military, shipping or fishing activity, due to acoustic interference, collision risk, and net entanglement. AUVs are also less well suited to tidally dominated shallow-water settings that have high levels of anthropogenic infrastructure and activity. This leads to requirement of development of dedicated path planning approaches for USVs against path planning approaches adopted for AUVs. In addition to that, most global path planning studies have not considered environmental effects and safety of the USV into account while designing planning approaches. The current paper adopts Dijkstra approach with a USV enclosed by a circular boundary as safety distance constraint on optimal path curvature. This resolves the problem of optimal path planning for a USV moving in a practical maritime environment leading to the generation of safer waypoints with conservation of optimality.

III. Dijkstra: Concept and Methodology

A. Concept of the proposed approach

Dijkstra is a graph-based approach applied to an environment represented as a connected graph to determine the shortest path between two nodes. There are many variants of Dijkstra algorithm but current study assumes an enclosed circular boundary around a USV as safety distance constraint as shown in Fig.1. The algorithm used in the present study is defined in Algorithm 1.

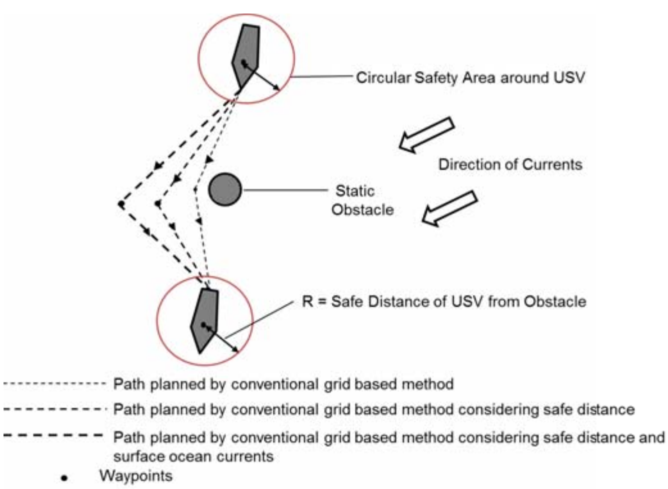

Fig. 1. A schematic showing the path generated by a convectional grid based path planner compared against the path generated by a grid based path planner by considering safety distance and sea surface currents

Mapping of the environment to convert working space into configuration space (Cspace) leads to quick execution of algorithms with practicable storage in computers. The current study adopts a popular mapping technique, regular binary grid, due to its effective resolution in grid-based path planners [16]. Portsmouth harbour is chosen as an area of study to understand the effectiveness of the proposed approach in path planning of USVs as shown in Fig.2. An 800x800 pixel map is chosen for the current study where each pixel is equal to 3.6 m.

The Dijkstra algorithm on a gridded map is restricted either to a 4-connectivity or 8-connectivity as shown in Fig.3, based on the resolution required, where each cell in Cspace is evaluated by a value of :

$$f(n) = g(n) \tag{1}$$

where, $g(n)$ is the length of the path from the initial state to goal state through a selected sequence of cells. The cell with lowest value of $f(n)$ is chosen as the next one in sequence. The advantage of modifying distance in Dijkstra gives the flexibility to modify navigation in terms of safety distance [17].

Fig. 2. Satellite image of Portsmouth Harbour and its corresponding binary image (Source: *Google Maps*)

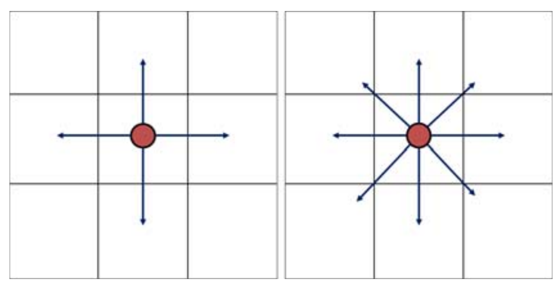

Fig. 3. Schematic of 4-connectivity and 8-connectivity in Cspace

B. Assumptions in the proposed approach

USV path planning is complex and needs a number of simplifications to reduce the complexity of the problem [18]. Following assumptions have been made in the current study :

1) The current study considers confined sea environment near to Portsmouth harbour where temporal and spatial variability in sea environment is considered quasi-static for the period of USV voyage.
2) The current study assumes that position and velocity of the moving obstacle in the Cspace is known from a Kalman filter and considered as a grid point on the map and modelled as an ellipse as per recommendations of IMO [19].

Algorithm 1: Constrained Dijkstra Algorithm

```
Data: start, goal(n), h(n), expand(n)
Result: Path
Begin;
if goal(start) = true then
    return makePath(start)
end
open ← start
closed ← ∅
while open ≠ ∅ do
    sort(open) ;
    n ← open.pop() ;
    kids ← expand(n) ;
    forall kid ∈ kids do
        kid.f ← (n.g + 1);
        if goal(kid) = true then
            return makePath(kid);
            if kid ∩ closed then
                open ← kid;
            end
            forall kid ← safetyDistance(pixels) do
                open ← kid;
            end
        end
    end
    closed ← n
end
return ∅
```

3) USV is assumed to proceed in a forward direction with a constant speed with no sway motion being considered during the search process.
4) The current study assumes that reactive collision avoidance is already on board to deal with collision avoidance problem in presence of moving obstacles in a near field scenario.

C. Methodology

The methodology adopted in the current study is shown through a schematic shown in Fig.4. The information on surface currents, moving obstacles and topography of the study area is used to define the map in form of a graph. The proposed study deals with inclusion of a safety distance criterion in the Dijkstra approach for USV path planning.

IV. Simulation Results

The proposed approach is simulated using C++ and OpenCV. All simulations are performed on a PC with *Microsoft* Windows 7 as OS with Intel i5 2.70 GHz quad-core CPU and 16 GB RAM. The simulations were repeated for 500 times, in terms of computational time, to account for variable computational power in OS Windows. The average time from all repetitions was calculated for proper verification of proposed approach.

A. Benchmarking safety distance

The proposed study deals with the inclusion of a safety distance criterion in the Dijkstra approach towards USV path planning. In order to benchmark the safety distance approach and to decide upon an optimum value of safety distance, four arbitrary values, 10, 20, 30 and 40 pixels are taken as safety distance on a grid map (as shown in Fig.2) and compared in terms of computational time. The start and goal states used in benchmarking the safety distance and towards simulating Dijkstra approach under static and partially dynamic environment is shown in Fig.5.

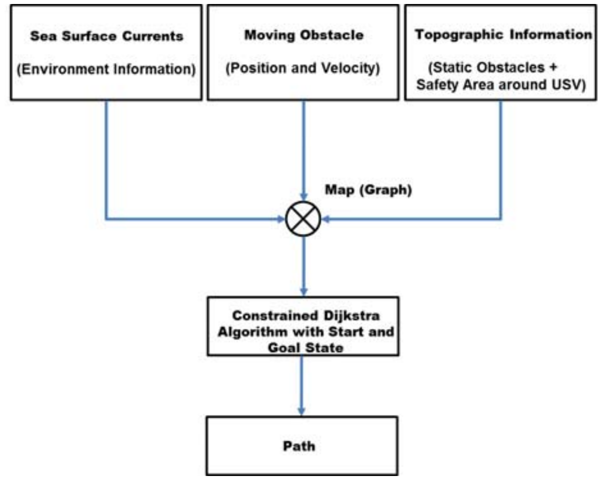

Fig. 4. Schematic of the proposed path planning system

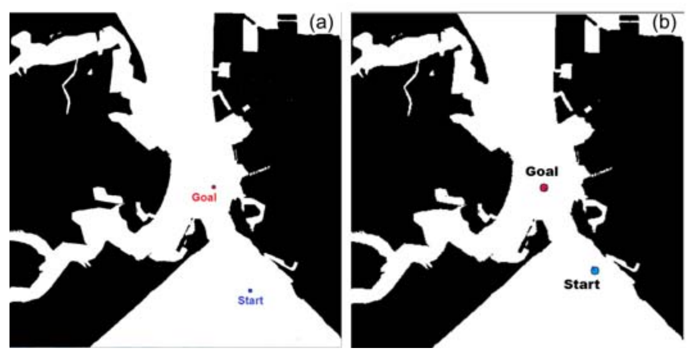

Fig. 5. Binary map with start and goal states for (a) benchmarking the safety distance criterion and (b) simulating Dijkstra approach for static and partially dynamic environment

Fig.6 shows the comparison of the Dijkstra approach with chosen safety distance values in terms of computational values and path length. Fig.7 shows the path generated from chosen safety distance values. The result shows that on a special Euclidean (*SE (2)*) grid map, larger safety distance produces optimal path with less computational effort. This is due to the fact that search process explores a lesser number of nodes with larger safety by pruning the search domain. The results also show that no loss of optimality happens while the search space is pruned since same path length is observed for all safety distance values.

Since the current study considers a narrow channel of Portsmouth harbour for path planning of USV, it becomes necessary to choose a safety distance where a proper trade-off between computational time and a safe distance from an obstacle can be maintained. Therefore, a 20-pixel safety

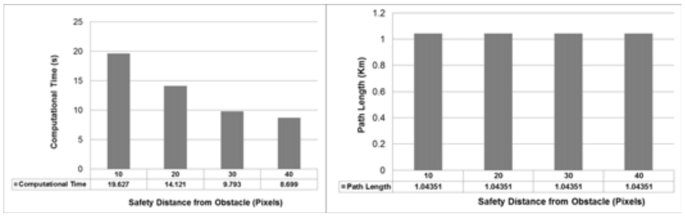

Fig. 6. Compared computational time and path length for chosen safety distance values using Dijkstra approach

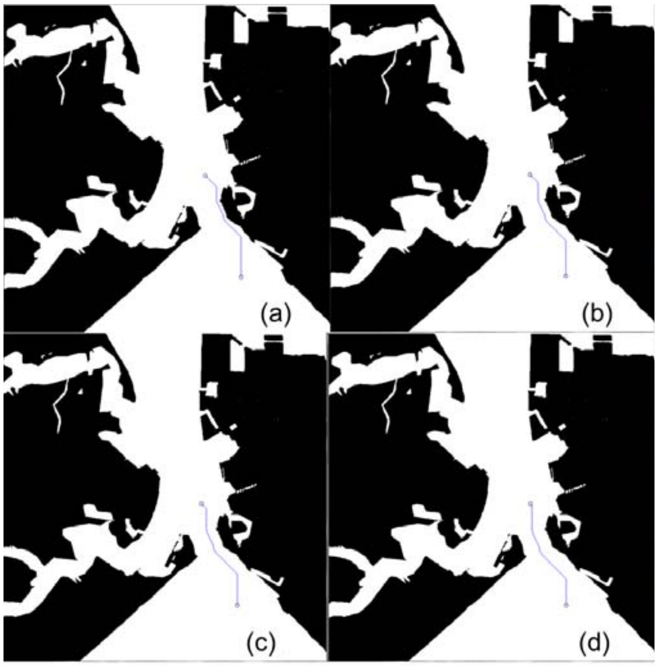

Fig. 7. Comparison of paths obtained with chosen safety distance of (a) 10 (b) 20 (c) 30 (d) 40 pixels

distance (72 m on real map) has been chosen for the present study. This value also provides enough time for local reactive techniques for collision avoidance in the case where one or more moving obstacles are detected in the operational domain of the USV.

B. Constrained Dijkstra approach with partially dynamic environment

In order to understand the effectiveness of the proposed approach, simulations are conducted in binary maps of the Portsmouth harbour, comprising of static and moving obstacles, together termed as, partially dynamic environment. A single moving obstacle, moving in a straight line, whose velocity and heading as defined in Fig.8 (a) has been incorporated into the binary map with each instantaneous position of the moving obstacle getting updated at a frequency of 0.2 Hz. Modelling of dynamic obstacles on a map for maritime path planning is defined in terms of the velocity of the moving obstacle in the maritime environment. [20] has suggested a circular shape for slow-moving obstacles and elliptical shapes for fast moving obstacles to incorporate the uncertainty of the moving obstacle in graph-based heuristic approaches. Therefore, an elliptical shape has been adopted in the current study as shown in Fig.8(b).

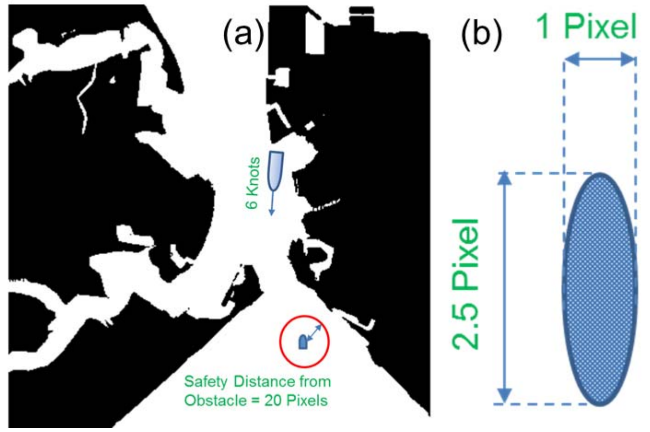

Fig. 8. (a) Binary map of the simulation area showing velocity and heading of the single moving obstacle (b) Dimension of the elliptical domain representing the single moving obstacle in the binary map

The result presented in Fig.9 shows the path generated by the proposed approach at different mission start time of the moving obstacle. Path length and computational time are computed for each start time of the mission and results are shown in Fig.10. Although not much difference have been found in the computational time to determine the path in the map, a decrease in path length has been found for the case where close encounter situations has been observed i.e. for mission start time of 40 and 50 seconds. This is owing to the fact that, algorithm prune the search space and less number of nodes are available to determine path leading to lower values of the Euclidean distance. This Euclidean distance is the main parameter to determine the value of $g(n)$.

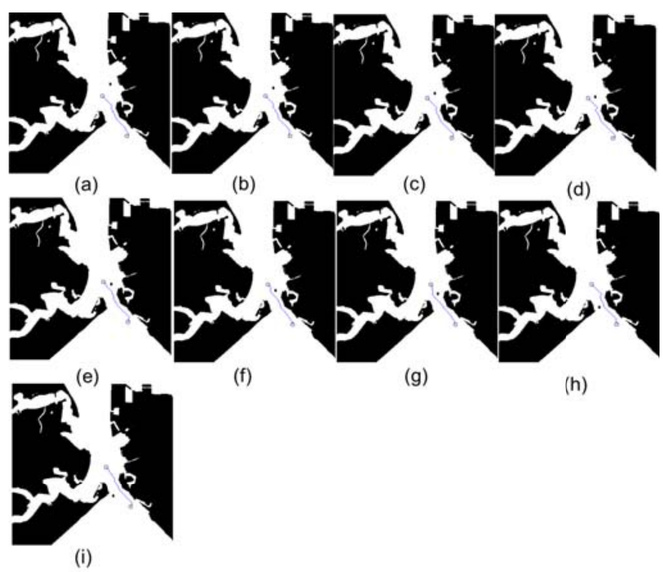

Fig. 9. Comparison of paths obtained with different mission start time (a) 0 (b) 10 (c) 20 (d) 30 (e) 40 (f) 50 (g) 60 (h) 100 (i) 120 seconds

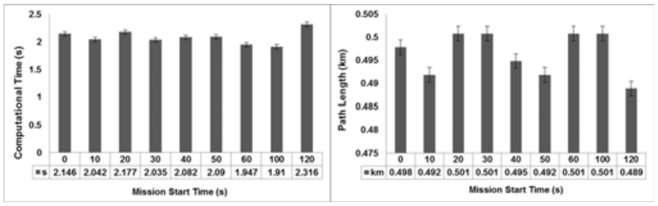

Fig. 10. Comparison of computational time and path length obtained with different mission start time (a) 0 (b) 10 (c) 20 (d) 30 (e) 40 (f)50 (g) 60 (h) 100 (i) 120 seconds.

C. Constrained Dijkstra approach with environmental disturbances

Ocean environmental effects can be bifurcated into three streams, as the additive and multiplicative disturbances on vehicle hull, namely, wind, waves and ocean currents [21]. Wind load is generally ignored in path planning since USVs have a high draft compared to an air projection area and operations are generally restricted in an environment with wind speed less than 10 m/s [12]. In order to simulate the motion of USVs, it is generally assumed that wave loads account for fluctuating pressure distribution below the water surface and water surface remains unaffected [21]. Hence wave loads become more significant in dynamic positioning than path planning. Wind-generated currents have the highest significance on path planning and waypoint optimisation. Since the Earth is rotating, the Coriolis force turns major currents to the right in the northern hemisphere while opposite in southern hemisphere [21].In general, ocean currents are provided in a NetCDF data format by various meteorological agencies around the world. Such data obtained from satellites have a resolution of 2 km [22] while the range of most navigation devices is less than 5 nmi which makes such data low in precision and not suitable for USV path planning. Hence, the synthetic vector field of moderate and strong intensity is created within the map to verify the effect of current on optimal path planning. Real ocean currents are multi-directional and irregular, spatially and temporally. In the present study, the current effect on USV path planning is simplified as a constant disturbance by assuming the current to be unchanged over a period of time [23]. Two current scenarios, a moderate current intensity of 1.5 m/s and a strong current intensity of 2.5 m/s is considered for the present study. These values are chosen on observation of high-speed currents of 2 to 3 m/s in coastal regions [21].

In order to understand the upstream and downstream effects of current on path planning, clockwise and anti-clockwise directions of chosen intensity values are taken in the present study. Fig.11 shows the path obtained by the proposed approach with currents moving in the anti-clockwise and clockwise direction with the intensity of 1.4 m/s. The path length and computational time are compared for both scenarios shown in Fig.11 and results are presented in Fig.12. The results show that when the USV operates in downstream currents, it has to cover a larger distance in the current while a smaller distance is observed in upstream currents. This is due to the fact that presence of downstream currents in the USV voyage creates larger forces in the sway motion, directing the USV to move closer to the shore line (as seen in Fig.11(a)), which leads to the generation of a path with a longer curvature. In terms of computational time, a similar trend has been observed under influence of sea currents.

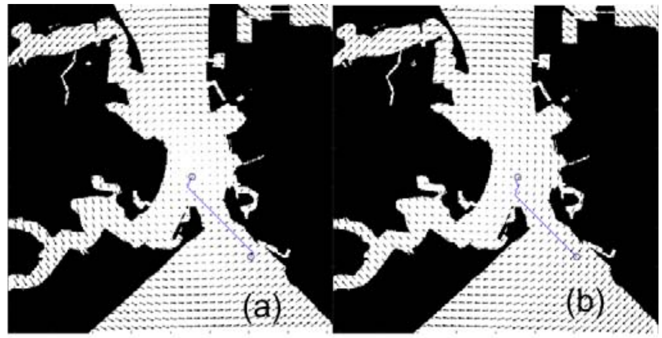

Fig. 11. Comparison of paths obtained for currents moving with intensity of 1.4 m/s in (a) anti-clockwise and (b) clockwise direction.

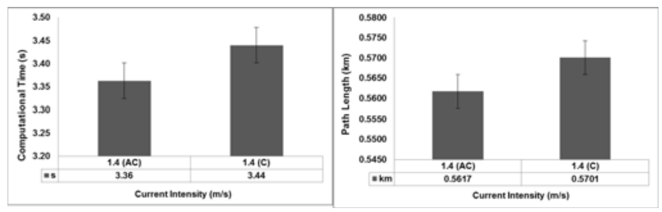

Fig. 12. Comparison of computational time and path lengths obtained for currents moving with intensity of 1.4 m/s in anti-clockwise (AC) and clockwise direction (C).

Along the same line, currents of 2.5 m/s are considered to understand the path planning pattern of USV under influence of strong ocean currents. Fig.13 shows the path obtained by the proposed approach with currents moving in the anti-clockwise and clockwise direction with the intensity of 2.5 m/s. The path length and computational time are compared for both scenarios shown in Fig.13 and results are shown in Fig.14. In this case, a similar pattern as found with 1.4 m/s has been observed. In terms of current intensities of different magnitude moving in the same direction, it has been found that currents of higher magnitude are more favourable in minimizing energy usage for USV voyage with a no substantial increase in computational effort. This leads to the fact that proposed approach can assist USV in utilizing the ocean environment intelligently to minimize energy usage by integrating current information with path planner.

V. Conclusions

In this paper, a constrained Dijkstra approach for optimal path planning of USVs in a confined maritime environment is proposed. The objective of generating safer way points by keeping a safe distance from the obstacle was evaluated in simulations, conducted in various environments comprising of the static obstacle, moving obstacle and sea surface currents of different intensities. The upstream and downstream effects of sea surface currents were also evaluated and analysed. The simulation results show that the present approach generates safer way points for USV voyage in a computationally efficient manner with no loss of optimality. The approach is found to be robust, computationally efficient and can be extended for real-time path planning of USVs in confined water. In conclusion,

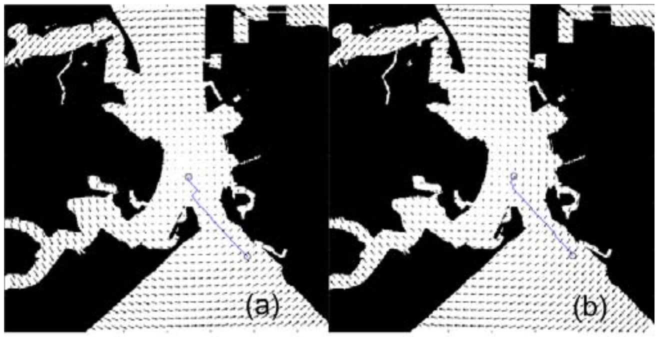

Fig. 13. Comparison of paths obtained for currents moving with intensity of 2.5 m/s in (a) anti-clockwise and (b) clockwise direction.

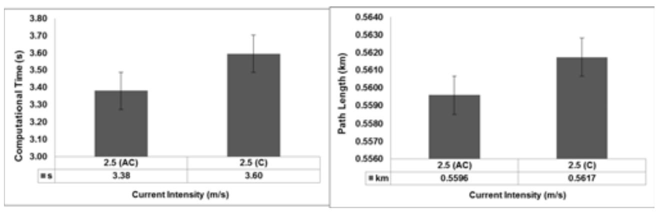

Fig. 14. Comparison of computational time and path lengths obtained for currents moving with intensity of 2.5 m/s in anti-clockwise (AC) and clockwise direction (C).

it is considered, such an optimal approach is suitable for global path planning of USVs. In future work, it is planned to extend the work in the development of a path follower approach working in conjugation with proposed approach for a reactive path planning in scenarios involving close encounters. Another extension of the present work lies in considering heading angle constraint for USV, in such cases, where, the path length is more important than computational time. This converts the problem from a *SE(2)* to a *SE(3)* path planning approach.

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